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Coagulation and Precipitation of Selected Metal Ions from Aqueous Solutions

Research Triangle Inst, Research Triangle Park, NC

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16. ABSTRACT The report gives results of laboratory jar tests to develop data on the removal from aqueous solution of 12 metal ions of environmental concern. The project, of very limited scope, provides initial screening data only: coagulants were evaluated at only two dose levels (1.1 and 1.5 stoichiometric), no combinations of metals or coagulants were evaluated, and no attempt was made to optimize precipitation conditions. The 12 metal ions were: Al(+3), Be(+2), Bi(+3), Cr(+3), Mo(+3), Sb(+3), V(+3), Zn(+2), Ti(+3), Se(+4), As(+3), and As(+5). Treatment chemicals used were lime, sodium sulfide, alum, and ferrous sulfate. Cr(+3), Al(+3), and Ti(+3) concentrations were reduced to below 0.5 mg/l at pH 8 by lime addition. Alum was effective for Ti(+3) removal (probably due to pH effects) and marginally effective for V(+3) and As(+5). Be(+2), Bi(+3), Zn(+2), and Ti(+3) were reduced to below 1 mg/l by sodium sulfide treatment. Ferrous sulfate was not effective in removing Sb(+3), Se(+4), or As(+5). Additional treatment with a flocculent-coagulant (e.g., organic polymer) may be required for the consistent removal of the fine suspension formed by some of the metal ion-coagulent systems tested.

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Solutions	Flocculents	Aqueous Solutions	
Precipitation		Sodium Sulfide	
Coagulants			06O, 11G

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Coagulation and Precipitation of Selected Metal Ions from Aqueous Solutions

by

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ABSTRACT

Laboratory jar tests were conducted to develop data on the removal from aqueous solution of 12 metal ions of environmental concern. The project, which was of very limited scope, provides initial screening data only. Thus, coagulants were evaluated at only two dose levels (1.1 and 1.5 stoichiometric), no combinations of metals or coagulants were evaluated, and no attempt was made to optimize precipitation conditions. The metal ions tested were: Al^{+3}, Be^{+2}, Bi^{+3}, Cr^{+3}, Mo^{+3}, Sb^{+3}, V^{+3}, Zn^{+2}, Ti^{+3}, Se^{+4}, As^{+3}, As^{+5}. Treatment chemicals used were: lime ($Ca(OH)_2$), sodium sulfide (Na_2S), alum ($AlK(SO_4)_2$), and ferrous sulfate ($FeSO_4$).

Chromium, aluminum, and titanium concentrations were reduced to below 0.5 mg/ℓ at pH 8 by lime addition. Alum was effective for titanium removal (probably due to pH effects) and marginally effective for vanadium and arsenic (+5). Beryllium, bismuth, zinc, and titanium were reduced to below 1 mg/ℓ by sodium sulfide treatment. Ferrous sulfate was not effective in removing antimony, selenium, or arsenic (+5).

Additional treatment with a flocculent-coagulant, i.e., organic polymer, may be required for the consistent removal of the fine suspension formed by some of the metal ion-coagulant systems tested.

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1.0 INTRODUCTION

The requirements of the 1977 Amendments to the Clean Water Act emphasize the control of "Toxic" or "Priority Pollutants." In addition to the 13 metals designated as toxic and which are to be controlled by Best Available Technology Economically Achievable regulations that industry must meet by July 1, 1984, there are other metals and non-metals of environmental and health concern.

Although a number of highly effective methods continue to become available for removal of heavy metals from wastewater, chemical precipitation is currently the most commonly used and practical technique and is possibly the best approach for coping with the metals removal problem up to and including 1984.

The purpose of this project was to develop specific data for incorporation into a wastewater treatability model. As such, the scope of work was specific and limited. Each metal ion was to be treated with a specific chemical at two dose levels (1.1 and 1.5 stoichiometric) with the final pH in the range 6-9. RTI also evaluated some other pH's and chemicals where these specified conditions proved to be inappropriate.

All experiments were simple jar tests using analytical grade reagents and distilled water as the medium. We recognize that the variable chemical environment found in actual wastewater can affect the removal of metal ions present. However, to provide a consistent data base for use in the model, this variability was reduced substantially by using distilled water.

Section 2 of this report summarizes the data obtained and conclusions that can be drawn. Section 3 presents some background information that was obtained on the metal ions and coagulation methods tested. The test procedures and test results are presented in Section 4.

2.0 SUMMARY AND CONCLUSIONS

Table 1 summarizes the test data obtained. The first two columns give the metal ion and coagulant(s) tested. Columns three and four give the stoichiometric ratio (see Section 3) for the coagulants and the final pH, respectively. The fifth column gives the concentration of metal ion remaining (typically 100 mg/ℓ initially) in the solution after filtration by a Whatman No. 40 filter (medium porosity) which may be similar to that expected from clarification and sand filtration. The last column gives the metal ion concentration obtained after washing the precipitate, suspending it (shaken by hand at infrequent intervals) in water for 24 hours, and filtering through a 0.8 μ millipore filter. This information is useful for situations where physical-chemical sludges generated must be washed before disposal and as an estimate of the leachability of the sludge.

The data show that pH adjustment (lime addition) is effective for the removal only of Al^{+3}, Cr^{+3}, and Ti^{+3}. Alum is effective for the removal of Ti^{+3}, probably due to pH effects, and marginally effective in the control of V^{+3} and As^{+5}. Removal of Be^{+2}, Bi^{+3}, Zn^{+2}, Ti^{+3} was effected by Na_2S additions. Ferrous sulfate was not effective for the removal of Sb^{+3}, Se^{+4}, or As^{+5}. Mo^{+3}, Sb^{+3}, Se^{+4}, As^{+5}, and As^{+3} were not effectively removed by the coagulants used for these ions (Mo^{+3} and As^{+3} were tested only with Na_2S; all coagulants were used with the remaining three) under the conditions used.

Aluminum hydroxide becomes more soluble as the pH is raised above 8. Therefore, optimum control will be obtained between pH 5 and pH 7. Several of the test solutions, most notably Al, Cr, and Zn, appeared to be somewhat turbid after filtration. Some of these were reanalyzed after standing for one day. The original Zn solution had been discarded before we observed that some of the solutions cleared on prolonged standing. Duplicate experiments were performed and the solution allowed to stand 3 hours before being filtered. In all cases a substantially lower metal concentration was obtained.

This indicates that some of the precipitate formed is very finely divided. To adequately remove the metals from solution, particularly when lime or Na_2S is used, may require the use of an additional coagulant, i.e., organic polymer.

It will also be observed that a number of cases occurred where the metal concentration was higher from the resuspended precipitate filtrate than in the original test solution filtrate. The effect is apparently not due to suspended solids since the original filtrate passed through a medium porosity filter, Whatman 40, whereas the resuspended particulate filtrate passed through a fine filter, 0.8 μ millipore. When the precipitate was washed, ions present in the original test solution were removed. Thus, one might conclude that these ions reduce the solubility of the precipitate and/or effect the desorption of the metal from the precipitate. This implies that some precautions should be taken in the washing and/or disposal of these sludges.

TABLE 1. SUMMARY OF RESULTS

Metal	Coagulant	Stoichiometric Ratio	Final pH	Filtrate mg/ℓ	Metal Solubility from Solids, mg/ℓ
Al^{+3}	$Ca(OH)_2$	-	7.0	5 (0.4)*	< 0.1
		-	8.0	0.4	1.1
		-	9.0	31 (20)*	
		-	10.0	48	6.4
Be^{+2}	Alum	1.1	7.3	> 50	16
		1.5	6.9	16	21
	$Ca(OH)_2$	-	8.0	~100	
	Na_2S	1.1	8.0	0.3	0.2
Bi^{+3}	Na_2S	1.1	8.9	< 0.03	0.05
		1.5	9.2	< 0.03	< 0.03
		1.1	8.0	< 0.5	
		1.5	8.0	2.5	
Cr^{+3}	$Ca(OH)_2$	-	7.0	10	< 0.1
		-	8.0	0.6	< 0.05
		-	9.0	12 (0.4)*	
		-	10.0	0.12	< 0.05
Mo^{+3}	Na_2S	1.1	7.5	No reaction occurred	
Sb^{+3}	Alum	1.1	7.2	22	8.4
		1.5	8.3	12	13
	$Ca(OH)_2$	-	8.0	~ 50	
	Na_2S	1.1	6.6	13	
	$FeSO_4$	1.1	8.0	10	
V^{+3}	Na_2S	1.1	8.5	> 50	1.7
		1.5	8.5	> 50	1.6
	$Ca(OH)_2$	-	8.0	32	
		-	10.0	27	
	Alum	1.1	7.0	20	

*Value obtained after one day aging.

(Continued)

TABLE 1. (Continued)

Metal	Coagulant	Stoichiometric Ratio	Final pH	Filtrate mg/ℓ	Metal Solubility from Solids, mg/ℓ
Zn^{+2}	Na_2S	1.1	8.5	1.2	0.7
		1.5	7.0	> 50	1.1
		1.1	8.0	0.07	5
		1.5	8.0	0.6	5
Ti^{+3}	Alum	1.1	8.6	< 0.5	
		1.5	7.3	< 0.5	
		1.1	7.0	< 0.1	0.2
	Na_2S	1.1	8.8	< 0.5	
		1.1	8.6	< 0.5	
		1.1	8.0	0.2	0.8
		1.5	8.0	0.3	0.4
	$Ca(OH)_2$	-	8.0	< 0.1	< 0.1
Se^{+4}	Na_2S	1.1	8.0	> 50	0[#]
		1.5	8.5	> 50	0[#]
	$Ca(OH)_2$	-	10.0	~100	
	Alum	1.1	7.2	~100	
	$FeSO_4$	1.1	8.0	~100	
As^{+5}	Na_2S	1.1	5.5	~100	
		1.5	9.6	~100	
	$Ca(OH)_2$	-	8.0	39	
	Alum	1.1	7.0	6.0	
	$FeSO_4$	1.1	8.0	~100	
As^{+3}	Na_2S	1.1	5.0	25	
		1.5	5.5	18	

[#]Probably indicates no Se in the precipitate.

3.0 BACKGROUND INFORMATION

A number of literature sources, listed at the end of this section, were consulted to determine appropriate precipitation conditions and other required information. The data accumulated is not a complete review of the literature available on the subject.

Al^{+3}

$Al(OH)_3$ is amphoteric (soluble at both low and high pH). The solubility product is about 2×10^{-33} (5×10^{-8} mg/ℓ Al) at pH 7. Aluminum sulfide cannot be prepared in aqueous solution.

Be^{3}

$Be(OH)_2$ is amphoteric. The sulfide reportedly decomposes in aqueous solution. The sulfate is very water soluble.

Bi^{+3}

The hydroxide is not amphoteric. The water solubility is about 0.0014 gm/ℓ (1.1 mg/ℓ Bi). The sulfide can be formed in aqueous solution and has a solubility of about 0.00018 gm/ℓ (0.14 mg/ℓ).

Cr^{+3}

The "hydroxide" is thought to be merely a hydrated form of the oxide. The compound is amphoteric dissolving in excess strong base. The approximate solubility is 0.00064 mg/ℓ. The sulfide cannot be made in aqueous solution. The sulfate is very water soluble.

Mo^{+3}

The hydroxide solubility is about 2 gms/ℓ (1300 mg/ℓ Mo^{+3}). The sulfide is slightly soluble in water.

Sb^{+3}

The oxide is amphoteric. The sulfide can be formed in acid solution (up to about pH 6) and has a solubility of about 0.0018 gm/ℓ (1.3 mg/ℓ Sb). The sulfide is soluble in neutral to alkaline

solutions and in solutions containing excess alkali sulfide (Na_2S).

V^{+3}

The oxide is basic (soluble in acid solution) and slightly soluble in water. Although the sulfide is insoluble in water, it is soluble in alkali sulfides.

Zn^{+2}

The hydroxide is amphoteric and when formed in aqueous solution forms a gelatinous precipitate. The solubility product is about 2×10^{-14} indicating the hydroxide is slightly soluble in water. The sulfide is white and has a solubility product of about 1×10^{-23}. ZnS(α) has a water solubility of 0.0069 gm/ℓ (4.6 mg/ℓ Zn) while ZnS(β) has a solubility of 0.00065 gm/ℓ (0.44 mg/ℓ Zn). The sulfide is soluble at pH less than 6.

Se^{+4}

The oxide is very water soluble. The sulfide is insoluble in water but dissolves in excess sulfide reagent.

As^{+3}, As^{+5}

The arsenic oxides are quite soluble in water. Arsenic(V) sulfide has a water solubility of 0.0014 gm/ℓ (0.6 mg/ℓ As) and arsenic (III) sulfide's water solubility is 0.0005 gm/ℓ (0.3 mg/ℓ As). Both sulfides are soluble at pH's above 6 and also are soluble in excess alkali metal sulfide (Na_2S).

Sources

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Fundamentals of Analytical Chemistry, Skoog and West, Holt, Rinehart and Winston, Inc., 1963.

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4.0 TEST DATA

4.1 REAGENTS AND SOLUTIONS

All reagents used were analytical grade. All test solutions, except molybdenum and bismuth, were prepared containing 100 mg/ℓ of the metal ion. Lime ($Ca(OH)_2$) and ferrous sulfate ($FeSO_4 \cdot 7\ H_2O$) were added as dry powders. Alum ($AlK(SO_4)_2 \cdot 12\ H_2O$) was weighed out before each test and dissolved in 30 ml of water before addition. A stock solution, prepared before each series of tests, of sodium sulfide ($Na_2S \cdot 9\ H_2O$) containing 10 gms/ℓ was added to the test solutions using pipets.

The test solutions were prepared as follows:

Aluminum - Al^{+3}. 0.1000 gm of aluminum wire was dissolved in dilute (3N) HCl and diluted to 1 liter.

Beryllium - Be^{+2}. 2.0758 gms of $Be(NO_3)_2 \cdot 3\ H_2O$ (F.W. 187.07) was dissolved in water and diluted to 1 liter.

Bismuth - Bi^{+3}. 0.0853 gm bismuth metal was dissolved in dilute (3N) HNO_3 and diluted to 1 liter. Bi^{+3} concentration was 85.3 mg/ℓ.

Chromium - Cr^{+3}. 0.7695 gm $Cr(NO_3)_3 \cdot 9\ H_2O$ (F.W. 400.15) dissolved in water and diluted to 1 liter.

Molybdenum - Mo^{+3}. 0.2 gm $MoCl_3$ suspended in water for 24 hours, filtered and analyzed by A.A. Mo concentration was 5.0 mg/ℓ.

Antimony - Sb^{+3}. 0.1874 gm $SbCl_3$ (F.W. 228.11) dissolved in dilute HCl and diluted to 1 liter.

Vanadium - V^{+3}. 0.1471 gm V_2O_3 (F.W. 149.884) dissolved in dilute HNO_3 and diluted to 1 liter.

Zinc - Zn^{+2}. 0.1000 gm zinc metal dissolved in HCl and diluted to 1 liter.

Titanium - Ti^{+3}. 0.3220 gm $TiCl_3$ (F.W. 154.26) dissolved in dilute HCl and diluted to 1 liter.

Selenium - Se^{+4}. 0.1633 gm H_2SeO_3 (F.W. 128.97) dissolved in water and diluted to 1 liter.

Arsenic - As^{+5}. 100 ml of arsenic A.A. standard (1000 mg/ℓ) diluted to 1 liter.

Arsenic - As^{+3}. 0.1320 gm As_2O_3 (F.W. 197.84) dissolved in dilute HCl and diluted to 1 liter.

4.2 COAGULANT DOSAGE CALCULATIONS

Below are representative calculations of the coagulant dosage required for each coagulant used (except lime which was used for pH adjustment only).

Alum. Calculations were based on the assumption that the metal sulfate is formed simply to provide a consistent technique for alum addition. The assumption is not necessarily valid since metal ion removal probably takes place by adsorption on the aluminum hydroxide floc that forms. $2\ Be^{+2} + AlK(SO_4)_2 \rightarrow 2\ BeSO_4$. 500 ml of a 100 mg/ℓ Be^{+2} solution contains 50 mg Be^{+2}. 50 mg ÷ 9.012 gms/mole Be^{+2} = 5.548 millimoles/500 ml. Since the stoichiometric requirement is 0.5 millimole alum per millimole Be^{+2}, 5.548/2 = 2.774 millimoles alum required for stoichiometric addition. Therefore, for a 1.1 stoichiometric addition, 1.1 x 2.774 = 3.051 millimoles are required. Since alum has a formular weight of 474.39, one millimole is 0.4744 gm. 3.051 millimoles alum is 1.4476 gms.

The complete calculation is:

((50 mg ÷ 9.012 mg/millimole) ÷ 2) x 1.1 x 0.4744 gm/millimole = 1.4476 gms.

Na_2S. Calculations are based on the assumption the metal sulfide is formed. $Bi^{+3} + 1.5\ Na_2S{\cdot}9\ H_2O \rightarrow 1/2\ Bi_2S_3$. 500 ml of an 85.3 mg/ℓ Bi^3 solution contains 0.2058 millimole. Since 1.5 millimoles of the sulfide are required per millimole of Bi^{+3} and one millimole of $Na_2S{\cdot}9\ H_2O$ is 0.24018 gm, the sulfide dosage required for 1.1 stoichiometry is (1.1)(1.5)(0.2058)(0.24018) = 0.0816 gm. The sulfide stock solution (10 gms/100 ml) contains 0.1 gm/ml. Thus 0.816 ml is required for the test.

Ferrous Sulfate. The calculations assume the sulfate is formed (to provide a consistent basis for addition) although metal ion removal may actually occur by adsorption on the ferrous (-ic) hydroxide floc formed. $Sb^{+3} + 1.5\ FeSO_4{\cdot}7\ H_2O \rightarrow 1/2\ Sb_2(SO_4)_3$. 500 ml of a 100 mg/ℓ Sb^{+3} solution contains 0.4107 millimole. Since 1.5 millimoles of $FeSO_4\ 7\ H_2O$ weighing 0.2781 gm per

millimole are required per millimole of Sb^{+3}, (1.1)(1.5) x (0.4107)(0.2781) = 0.1885 gm $FeSO_4 \cdot 7\ H_2O$ are required for a 1.1 stoichiometric dosage.

4.3 TEST PROCEDURES

One liter of the metal ion solution was prepared as previously described. The solution was equally divided and placed in two 1 liter flasks. A magnetic stirrer and a pH measuring electrode were also placed in the flask. The initial pH was measured and adjusted as necessary using appropriate strength NaOH or HCl. The selected coagulant was then added and the solution rapidly agitated for about one minute. The pH was measured and adjusted as required. Stirring was then reduced to that required to keep the precipitate in suspension and maintained for 14 minutes. The suspension was then filtered through Whatman No. 40 filter paper. The filtrate was retained for atomic adsorption analysis. The solids collected were thoroughly washed with distilled water and resuspended (shaken by hand at infrequent intervals) in about 100 ml of distilled water. After 24 hours, this suspension was filtered through a 0.8 μ millipore filter and the filtrate retained for A.A. analysis.

Table 2 shows that the initial pH's were generally quite low compared to typical wastewater values. Operating in this manner, precipitates of $Al(OH)_3$ and $Fe(OH)_2$ did not form immediately when alum and ferrous sulfate were added. Since these compounds were soluble, they were completely mixed into the solution before the pH was raised to develop the floc. This technique could not be used with Na_2S because the H_2S which would be formed would escape from the solution.

Only the sulfide solution (and lime, of course) had any measurable effect on the initial pH. Addition of HCl was required to control the pH rise caused by the addition of this strong caustic solution.

4.4 ATOMIC ABSORPTION ANALYSIS

All analyses were completed on a Perkins-Elmer Model 603 atomic absorption instrument which has background correction. Air/acetylene or N_2O/acetylene flames were used as appropriate. A model 2100 Heated Graphite Furnace accessory was used for Ti, Mo as well as those metals having a concentration below 0.5 mg/ℓ. Electrodeless discharge lamps were used for As, Se, Sb, and Bi. Hollow Cathode lamps were used for other metals. Concentrations of the

metals in the test solutions were determined by comparison with known concentrations of the metals. In addition, the method of standard additions (adding a known amount of the test metal to the solution) was used to check the analytical results.

4.5 TEST RESULTS

Table 2 gives the test results and a comment on the precipitate formed. Unless otherwise indicated, the initial concentration of metal ion was 100 mg/ℓ.

TABLE 2. TEST RESULTS

Metal	Coagulant Type	Coagulant Dose	pH at Test Start	pH after Addition	Final pH	Filtrate Conc., mg/ℓ	Washed Filter Conc., mg/ℓ	Comment
Sb^{+3}	Alum	1.5	1.5	1.6	8.3	12	13	Fine white needles formed on addition.
Sb^{+3}	Alum	1.1	1.5	1.1	7.2	22	8.4	
Be^{+2}	Alum	1.1	3.3	3.3	7.3	> 50	16	Solids form at pH 4.5.
Be^{+2}	Alum	1.5	3.3	3.6	6.9	16	21	
Ti^{+3}	Alum	1.1	2.4	2.5	8.6	< 0.5		Light blue solids form on addition.
Ti^{+3}	Alum	1.5	2.4	2.6	7.3	< 0.5		
Cr^{+3}	Lime	-	3.2	10.0	10.0	0.12	< 0.05	Turbid at pH 5.7 fine dispersed solids.
Cr^{+3}	Lime	-	3.2	8.0	8.0	0.06	< 0.05	
Al^{+3}	Lime	-	1.5	8.0	8.0	0.4	1.1	Turbid at pH 6.
Al^{+3}	Lime	-	1.5	10.0	10.0	48	6.4	
Bi^{+3}	Na_2S	1.1	6.1	8.9	8.9	< 0.03*	0.05	Dark brown solids slow settling fines.
Bi^{+3}	Na_2S	1.5	5.8	9.2	9.2	< 0.03*	< 0.03	
Se^{+4}	Na_2S	1.1	6.2	8.0	8.0	> 50	0	Cloudy yellow suspension, probably sulfur.
Se^{+4}	Na_2S	1.5	5.7	8.5	8.5	> 50	0	
V^{+3}	Na_2S	1.1	6.1	7.6	8.5	> 50	1.7	Dark green-brown soln. no solids evident.
V^{+3}	Na_2S	1.5	6.2	8.0	8.5	> 50	1.6	
As^{+5}	Na_2S	1.1	5.6	6.4	5.5	∿100	-	Colorless, clear solution.
As^{+5}	Na_2S	1.5	7.4	9.6	9.6	∿100	-	

*Initial concentration 85 mg/ℓ.

(Continued)

TABLE 2. (Continued)

Metal	Coagulant Type	Coagulant Dose	pH at Test Start	pH after Addition	Final pH	Filtrate Conc., mg/ℓ	Washed Filter Conc., mg/ℓ	Comment
Ti^{+3}	Na_2S	1.1	7.1	9.7	8.8	< 0.5		White solids, turbid suspension.
Ti^{+3}	Na_2S	1.5	7.2	9.9	8.6	< 0.5		
Zn^{+2}	Na_2S	1.1	6.3	6.8	8.5	1.2	0.7	White solids, turbid suspension.
Zn^{2}	Na_2S	1.5	6.2	7.0	7.0	> 50	1.1	
Se^{+4}	Lime	-	3.3	9.8	9.8	∿100	-	Clear
Se^{+4}	Alum	1.1	3.3	3.3	7.2	∿100	-	Alum precipitate
V^{+3}	Lime	-	1.1	7.9	7.9	32	-	Brown solution, discrete particles.
Sb^{+3}	Lime	-	1.0	8.0	8.0	∿50		Slow settling white solids.
Be^{+2}	Lime	-	4.1	8.0	8.0	∿100		Light blue gelatinous precipitate.
As^{+5}	Lime	-	1.2	8.0	8.0	39		Milky colored suspension.
V^{+3}	Lime	-	8.0	10.0	10.0	27		No precipitate formed.
Cr^{+3}	Lime	-	3.5	9.0	9.0	12 (0.4)#		Filtered solution turbid but clears on prolonged standing.
Cr^{+3}	Lime	-	3.5	7.0	7.0	10	< 0.1	
Al^{+3}	Lime	-	1.5	7.0	7.0	5 (0.4)#	< 0.1	Milky, clears on standing.
Al^{+3}	Lime	-	1.5	9.0	9.0	31 (20)#		

#Concentration determined after one day settling.

(Continued)

TABLE 2. (Continued)

Metal	Coagulant Type	Coagulant Dose	pH at Test Start	pH after Addition	Final pH	Filtrate Conc., mg/ℓ	Washed Filter Conc., mg/ℓ	Comment
Ti^{+3}	Lime	-	2.5	8.2	8.2	< 0.1	< 0.1	White solids.
Ti^{+3}	Alum	1.1	2.5	7.0	7.0	< 0.1	0.2	Immediate solids formation.
V^{+3}	Alum	1.1	1.0	7.0	7.0	2.0		Brown solids, easily settled.
As^{+5}	Alum	1.1	1.0	7.0	7.0	6.0		Milky solution.
Zn^{+2}	Na_2S	1.1	6.6	9.8	8.0	0.07	5	Fluffy blue-white solids.
Zn^{+2}	Na_2S	1.5	5.6	10.3	8.0	0.6	5	
Mo^{+3}	Na_2S	1.1	5.4	8.8	7.5	5[†]		No reaction
Bi^{+3}	Na_2S	1.1	5.0	10.5	8.0	< 0.5		Reddish-brown solids easily settled.
Bi^{+3}	Na_2S	1.5	4.6	10.4	8.0	2.5		
Be^{+3}	Na_2S	1.1	3.8	6.8	8.0	0.3	0.2	Cloudy, poor settling.
Sb^{+3}	Na_2S	1.1	4.8 Held at 7		6.6	13		Orange, poor settling.
Ti^{+3}	Na_2S	1.1	5.8 Held at 8		8.0	0.2	0.8	Turbid, white solids.
Ti^{+3}	Na_2S	1.5	5.2 Held at 8		8.0	0.3	0.4	
Se^{+4}	$FeSO_4$	1.1	3.1	3.1	8.0	∿100		Iron hydroxide precipitate.

[†] Initial concentration 5 mg/ℓ.

(Continued)

TABLE 2. (Continued)

Metal	Coagulant Type	Coagulant Dose	pH at Test Start	pH after Addition	Final pH	Filtrate Conc., mg/ℓ	Washed Filter Conc., mg/ℓ	Comment
Sb^{+3}	$FeSO_4$	1.1	5.0	5.0	8.0	10		
As^{+5}	$FeSO_4$	1.1	5.1	8.0	8.0	~100		
As^{+3}	Na_2S	1.1	4.5	10	5.0	25		Cloudy, yellow solution, poor settling.
As^{+3}	Na_2S	1.5	3.5 Held at 6		5.5	18		